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ABSTRACT

Postural control is known to be the result of the integration and processing of various sensory inputs by the central nervous system. Among the various afferent inputs, the role of auditory information in postural regulation has been addressed in relatively few studies, which led to conflicting results. The purpose of the present study was to investigate the influence of a rotating auditory stimulus, delivered by an immersive 3D sound spatialization system, on the standing posture of young subjects. The postural sway of 20 upright, blindfolded subjects was recorded using a force platform. Use of various sound source rotation velocities followed bysudden immobilization of the soundwascompared with two control conditions: no sound and a stationary sound source.

The experimentshowed that subjects reduced their body sway amplitude and velocityin the presence of rotating sound compared with the control conditions. The faster the sound source was rotating, the greater the reduction in subject body sway.Moreover, disruption of subject postural regulation was observed as soon as the sound source was immobilized.

These results suggest that auditory information cannot be neglected in postural control, and that it acts as additional informationinfluencing postural regulation.

KEYWORDS

Posture, auditory perception, sound spatialization

INTRODUCTION

Postural regulation is the result of the dynamic processing of various sensory inputs by the central nervous system. Motor responses are continuously generated in reaction to this flow of information in order tostabilize the standing position (Maurer et al. 2006). Vestibular, proprioceptive and especially visual information are known to be the main afferent inputs involved in this regulation (Redfern et al. 2001). There is a substantial literature about interactions between vision and posture. For instance, it is well known that visual fixation may help subjects to stabilize (Kelly et al., 2008), whereas moving visual fields induce an increase inbody sway (Mergner et al. 2005).

Auditory information is rarely considered in the management of balance and posture, even though we are always surrounded by a dynamicauditory environment. The lack of interest shown by researchers regarding interactions between auditory information and postural control may be explained by the fact that our ability to locate sounds is less accurate than that for visual cues (Makous and Middlebrooks 1990). However, sound presents some specificities which could be important for postural regulation, and for motor control more generally. For instance, sound perception is not limited to forward space as with the visual system. It could lead to postural regulation even when the stimulus is behind the subject. In this way, the auditory environment may be seen as a rich source of information useful in balance control.

It has been shown that people are able to use auditory information in motor tasks. For example, a study by Stoffregen et al. (2009) showed that blindfolded subjects were able to correlate their head movements with the movement of theauditory environment surrounding them. In real life, auditory information is continuously integrated by people, and can become essential, as in the case of blind people's spatial orientation using echolocation (Kellogg 1962). Conversely, it is known that partial loss of hearing is responsible for deteriorated postural regulation (Era et Heikkinen 1985; Juntunen et al. 1987). Similarly, subjects deprived of natural auditory cues (placed in a soundproof room or wearing ear defenders) demonstrate greater body sway (Kanegaonkar et al. 2012).For all these reasons, it was decided to further investigate the relationship between sound perception and postural control.

Althoughauditory information seems to play a role in postural management, only a few studies have addressed this influence, and their results appear to be contradictory. A handful of studies have addressed the role of stationary sound on postural control. Easton et al. (1998) showed that auditory cues provided by two static sound sources to the right and left of a subject in Romberg stance[1] can slightly reducetheir body sway (by 10%, compared with 60% for visual cues).Contrary to these results, in two other studies abstract stationary sound was found to increase body sway in standing subjects, compared with no sound: first in the study by Raper and Soames (1991) involving pure tone or background conversation stimuli and then in the study of Park et al. (2009) involving pure tones at different frequencies and intensities.For their part, Palm et al. (2009) showed that musical auditory stimuli in headphones had no effect on the posture of standing subjects. A few other studies have addressed the effect of moving sound sources on postural balance. They also led to conflicting results. For instance, Soames and Raper (1992) placed loudspeakers at the four cardinal points around a standing subject. Then, they used sine waves or background conversation moving from side-to-side or from front-to-back as auditory stimulation. These moving sounds were found to induce increased subject body sway. Conversely, Agaeva and Altman (2005) used an array of loudspeakers in the sagittal plane. They found that sound bursts moving up and down allowed subjects to slightly reduce their body sway. Another study led by Tanaka et al. (2001) involved rotating white noise using 3D binaural spatialization over headphones. These rotating stimuli were found to disturb the postural regulation of elderly people in Romberg stance, when combined with deprivation of visual or somesthetic information. On the other hand, Deviterne et al. (2005) tested the effect of adding a cognitive load to the auditory information. They used amplitude panning with 4 loudspeakers to create rotating audio

[1]Heel-to-toe position

stimuli, whether carrying a meaningful message (recorded voice telling a short story) or not (simple sine wave). The meaningful message conditions were found to allow the elderly to better stabilize, inducing a decrease in their body sway.

In summary, the influence of sound on posture seems to be tenuous and highly dependent on experimental conditions. For instance, these conflicting results could be explained by the properties of the sound stimuli themselves. Indeed, sound has particularities and complexities that could be further explored in studies on sound and posture.

One of these features is the dynamic characteristic of sound, expressed in two aspects: morphology and spatial displacement. The morphology of sound can be perceptually defined by sound timbre and dynamics and their changes over time. It has been shown that changes in the morphology of a still sound source can evoke a wide range of motion of this source. For example, in a perceptual test led by Merer et al. (2008), subjects identified different kinds of motion(“rotate”, “fall down”, approach”, “pass by”, etc.) in a corpus of monophonic (so spatially still) sounds. In the present study, the focus is on the spatial displacement of the sound surrounding us. In real-life, our auditory environment is always moving with respect to ourselves. Thus, it is interesting to study the effect of a moving sound source on still subjects, which is common in real-life situations, and is providing more spatial information to subjects than stationary sound. Earlier postural studies involving a moving sound source, for which a brief overview has been given above, used simple trajectories, with a basic amplitude panning loudspeaker set-up. However, it can be imagined that realistic spatial immersion would better implicate subjects and influence their postural sway. For this reason, it was decided to work with a 3D sound spatialization system, which can simulate realistic three-dimensional sound displacement. To our knowledge, sound spatialization has only previously been used once in postural studies, by Tanaka et al. (2001). However, they worked with a binaural system with non-individualized head-related transfer functions (HRTF), which is known to result in perceptual distortions (Wenzel et al. 1993), and with headphones, which prevent perception of externalized sound.

The purpose of the study presented in this paper was to investigate the effect of sound perception on postural regulation, exploiting the dynamic attributes of sound through spatial displacement of a sound source. For this purpose, a postural test was set up involving the rotation of sound sources around standing subjects at various velocities, using the spatialization apparatus described in the methods.

METHOD

Subjects

The study group consisted of 12 men (25.2±3.9 years, 175.6±6.9 cm, mean±SD) and 8 women (24.9±3.3 years, 165.5±6.7 cm). All 20 subjects were physically active and reported no history of vestibular, visual or auditory disease. The subjects had their hearing checked, using a standard pure tone audiometry test, to determine whether it was within normal limits (able to hear tones above 60 dBA) prior to their inclusion in the study. All of them participated on a volunteer basis; they signed an informed consent form prior to testing. This study was performed in accordance with the ethical standards of the Declaration of Helsinki (revised Edinburgh, 2000).

Apparatus

The experimental set up is represented Figure 1. A third-order Ambisonic system was implemented in order to obtain moving sources. This system is based on the spherical harmonic decomposition of the sound field (Gerzon, 1985). It makes it possible to create a sound field around the subject and to produce a realistic sound immersion. The Ambisonicsystem was set up in a soundproof room (acoustically treated studio:reverberation time 0.3 s, background noise level18.5dBA). It comprised 16 loudspeakers (Yamaha Monitor Speaker MS 101 II), a MOTU PCI-424 sound card and control software using Max/MSP by Cycling'74. The loudspeakers were equally distributed on a virtual sphere of radius 1.10 m surrounding the subject. Sound generation, filtration and spatialization were real-time rendered using Max/MSP. By means of this technology, the displacement of a rotating sound source was simulatedin the horizontal plane around the subject.

Postural sway was determined from recordings of the three orthogonal ground-reaction forces (F_x, F_y and F_z) together with their associated moments about the three axes (M_x, M_y and M_z), using an AMTI Biomechanics Force Platform (model BP6001200-1000).

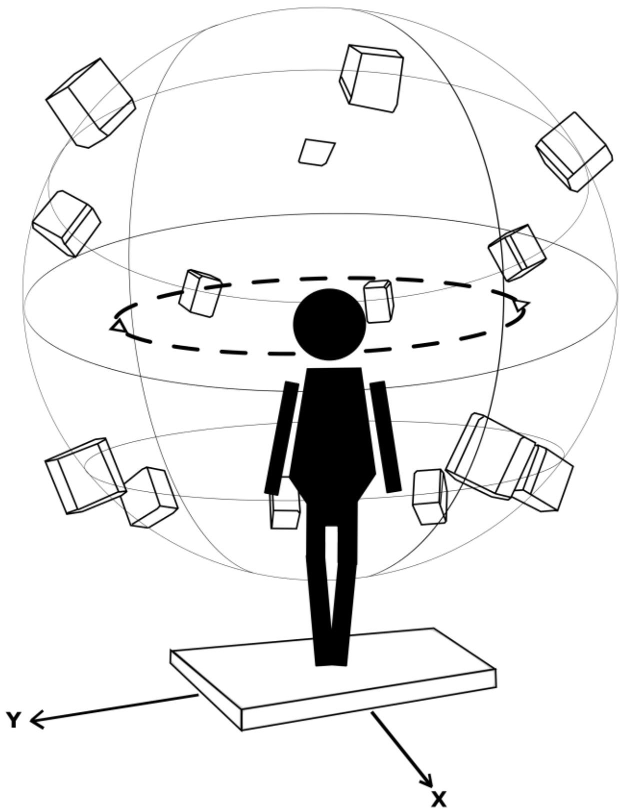


FIGURE 1: Experimental apparatus: the subject, who is standing on a force platform, is surrounded by the 16 loudspeakers of the Ambisonic system. The dashed line represents the simulated trajectory of the stimuli.

Auditory stimuli

The rotating auditory stimuli were low-pass filteredwhite noise. White noise is an abstract sound: it was chosen in order to avoid cognitive treatment or the affective responses associated with semantic or musical stimuli. Moreover, white noise is a wide-band sound: it is better localized by subjects because it stimulates all auditory localization cues:interaural time differences (ITD), interaural level differences (ILD), and spectral cues. The noise was low-pass filtered to match the spectral reproduction range of the Ambisonic system.

The intensity of the sounds was 83 dB SPL at the center of the system. The sound source described a circle of radius 1.10 m, at the height of the subject's ears and in the horizontal plane. Using this trajectory, various sound source velocities were tested: 20, 60, 180°/s,along with an acceleration from 20 to 180°/s.

Each of these four sound stimuli lasted 70 seconds and was divided into two parts. The sound source was first rotated for 50 seconds, then suddenly immobilized in front of the subject for a further 20 seconds. This immobilization of the sound enabled testing of the effect of a sudden change. In order to ensure that the sound source was directly in front of the subject after 50 seconds of rotation, the sound trajectories began at different azimuth angles depending on their velocity.

Procedure

Participants stood upright, barefoot, with feet together (well joined) on the force platform. Adhesive tape was used to mark the positions of the feet at the center of the platform, so that the same configuration could be precisely repeated for each trial. The experiment took place in the dark, and subjects were also blindfolded to ensure a complete suppression of visual information.

Participants began each trial by adopting the stance and positioning their arms at their sides, facing forward with their eyes closed and wearing the blindfold.

The instructions were to listen to the sound, without moving. Subjects were also asked to count the number of times they heard the sound completing a lap. None of the subjects was aware of the fundamental topic of the research, or even that they were involved in a postural measurement procedure. This enabled recording of the most natural postural regulation. Indeed, it is known that during quiet standing, attentional focus on one's own body sway detrimentally affects postural control (Vuillerme and Nafati 2007). Thus, for the subjects, the counting task was assumed to be the main purpose of the experiment. But it was only a secondary task, ensuring that subjects remain focused on the auditory stimuli. The subjects' counts were recorded for additional analyses if required.

Once they felt ready, subjects said "go!" and the experimenter simultaneously initiated data acquisition and auditory stimuli. The experiment included three blocks of four trials (four different sound stimuli repeated three times). Conditions were randomized within a block. Two control conditions (no sound, labeled NS, and a stationary sound in front of the subject, labeled SS) lasting 70 seconds were added twice, once before and once after the three blocks. Between each block, the participant stepped off the platform and sat comfortably for at least 3 minutes.

Data analysis

The data acquisition was set at a sampling frequency of 200 Hz. The position of the Center Of Pressure (COP) of subjects was calculated from the force and moment data.

Before any further calculation, COP data was lowpass filtered (2nd order Butterworth filter, 10 Hz cut-off frequency). Then, two representative sway parameters were calculated from this data:

• area within the sway path (mm^2), estimated by calculating the area of the 95% confidence ellipse based on the sample positions. It reflects the amplitude of sway: the larger the area, the less precise the postural control.

• sway velocity (cm/s):

$$v_{sway}(t) = f_s * \sqrt{\partial\, COP_x^{\,2} + \partial\, COP_y^{\,2}}$$

Two typical trends were observed on the sway velocity curves, represented on Figure2: an initial decrease in velocity during the first 10 seconds of trial, leading to relative stability; and a sudden increase in velocity when the sound source was immobilized at 50 seconds.

Two parameters were calculated to characterize these observations:

- the “time before stabilization”, T_{stab}. To calculate this period, the mean velocity on the stable part of the trial v_{stab} (between 20 and 50 seconds) was first calculated. $T_{stab}$was then defined as the time when the smoothed velocity curve first crossed the v_{stab} line.
- the "velocity leap", v_{leap}, calculated as the difference between the mean velocity before (from 40 to 50 seconds) and after (from 50 to 60 seconds) sound immobilization.

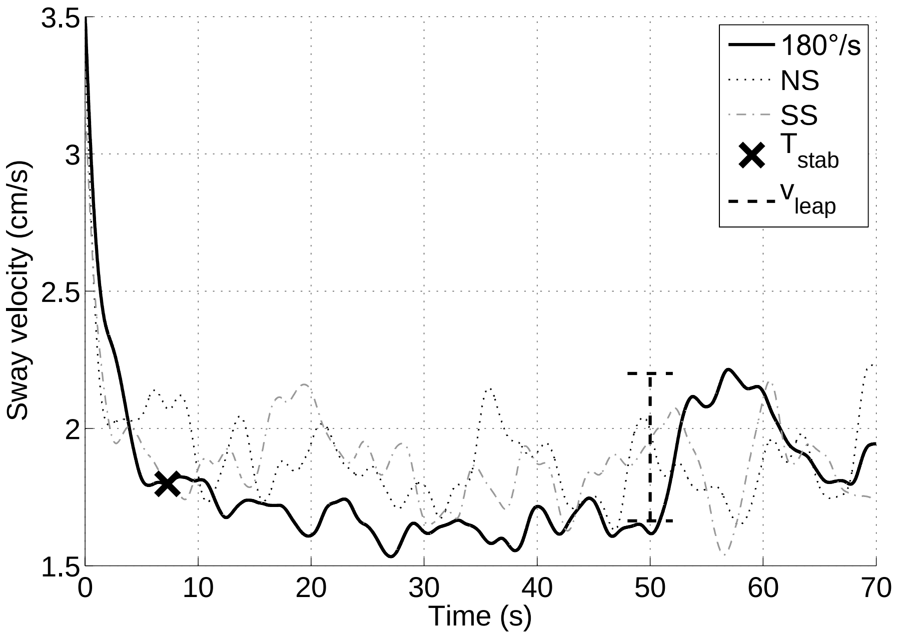


FIGURE 2: Velocity trends for 180°/s conditions and control conditions, and calculated parameters (mean over 20 subjects).

Moreover, sway area and mean sway velocity were calculated only on the stable part of the trial (between T_{stab} and the sound immobilization).
Each parameter was averaged over the three repetitions of each conditionand entered into a one-way repeated measures analysis of variance (ANOVA) with the conditions as the within-subject factor (six levels: the fourconditionsand the two control conditions). A least significant difference (LSD)testwas used for all post-hoc analysis.

RESULTS

Counting task

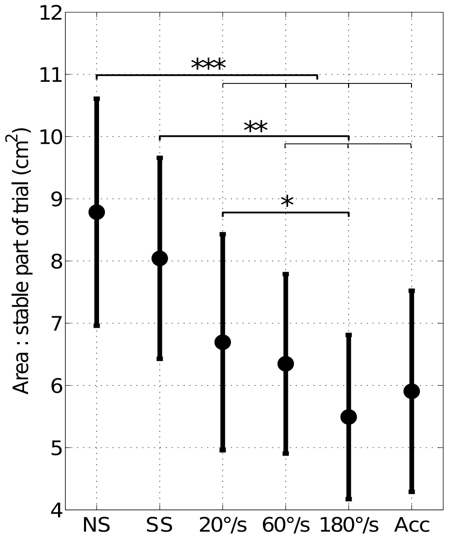
Subjects had to count the number of times the sound completed a lap and it was assumed by them to be the main task. For 63.1% of trials, counting was right; in 29.6% of trials, subjects were out by one lap, and in 4.17% of trials theywere out by two laps. These results show that the subjects were focused on the sound and were able to hear source displacement.

Area within the sway path

The results of the area within the sway path are presented Figure 3 and Table 1. The amplitude of subject body sway was smaller with a moving sound stimulus than for the two control conditions NS and SS. This difference was not observed for the last 20 seconds of trials, when the sound was immobilized. Moreover, a rotation velocity effect was observed: the faster the sound source was rotating, the smaller the area. The ANOVA revealeda significant effect for these conditions ($F_{5,95}$= 9.0981; $p < 0.001$). Post-hoc analysis showed significant differences between the two control conditions and the four moving sound conditions ($p<0.01$) and between 20°/s and 180°/s ($p < 0.05$).

	NS	SS	20°/s	60°/s	180°/s	Acc
Area (cm^2)	8.78 (4.16)	8.04 (3.69)	6.69 (3.96)	6.34 (3.29)	5.49 (3.01)	5.90 (3.69)
Mean velocity (cm/s)	1.87 (0.48)	1.85 (0.54)	1.80 (0.60)	1.74 (0.50)	1.67 (0.53)	1.69 (0.52)
T_{stab}(s)	3.84 (4.11)	5.96 (6.5)	6.93 (3.87)	6.89 (4.69)	7.75 (4.69)	7.47 (5.04)
v_{leap}(cm/s)	-0.036 (0.348)	0.027 (0.368)	-0.071 (0.276)	0.230 0.335)	0.368 (0.470)	0.359 (0.502)

TABLE 1: Mean (SD) values of the various parameters studied.



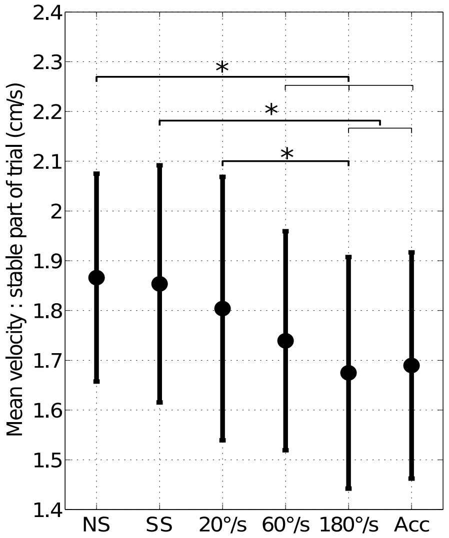


FIGURE 3: Left: Mean area within the sway path across subjects, between T_{stab} and the sudden change. Right: Mean sway velocity across subjects, between T_{stab} and the sudden change. Error bars represent 95% confidence interval. We can observe same tendencies on both figures: area and mean sway velocity are significantly higher for the two control conditionsno sound (NS) and with stationary sound (SS), compared to the moving sound conditions (* means $p < 0.05$, ** means $p < 0.01$, *** means $p < 0.001$)

Mean sway velocity

The same trends were observed for mean velocity as for area (Figure 3): subject body sway velocity was significantly smaller with moving sound stimuli than for control conditions ($F_{5,95}= 3.61$; $p < 0.01$), and smaller when rotation velocity increased. Post-hoc analysis showed significant differences between NS and 60°/s, 180°/s, Acc, between SS and 180°/s, Acc, and between 20°/s and 180°/s ($p < 0.05$).

Time period before stabilization T_{stab}

$T_{stab}$was 3.84 s for NS, 5.96 s for SS and around 7s for the four moving sound conditions. The ANOVA showeda close from significance effect of the condition on the time before stabilization ($F_{2,38}= 2.22$; $p = 0.059$).

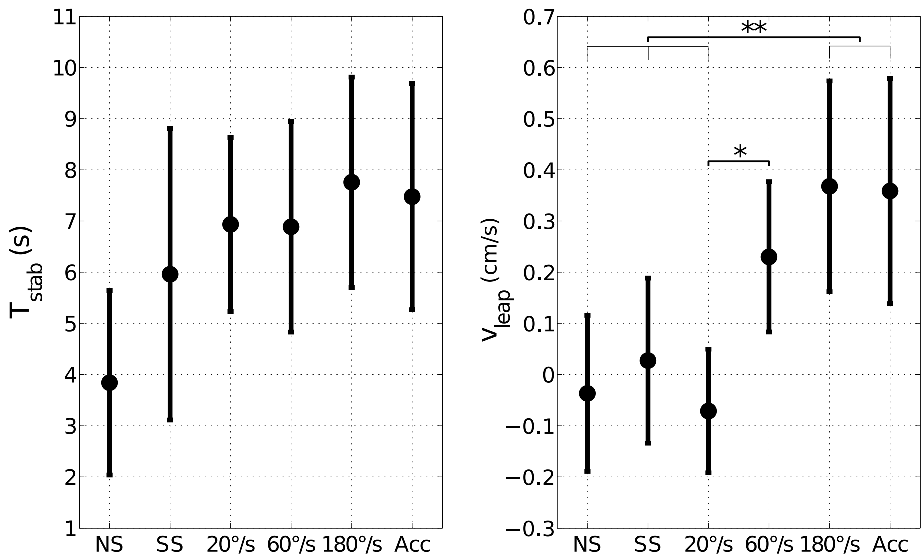


FIGURE 4: Velocity parameters. Left: Time before stabilization (T_{stab}). Right: Velocity leap (v_{leap})when the sound stops moving. Mean across 20 subjects. Error bars represent 95% confidence interval. (* means $p<0.05$; ** means $p<0.01$)

Velocity leap v_{leap}

As represented on Figure 4, the faster the stimulus was rotating at the sudden immobilization, the larger the velocity leap. For the two control conditions (no sudden change)and the condition with the lowest rotation speed (20°/s), v_{leap} was around zero. There was no difference between the 180°/s conditions and acceleration conditions: the stimuli were rotating at the same speed at the time of sudden immobilization. The ANOVA showed that conditions had a strong effect ($F_{5,95} = 5.5331$; $p < 0.001$) and post-hoc analysis showed significant differences between NS, SS and 60°/s, 180°/s, Acc ($p<0.01$) and between 20°/s and 60°/s ($p<0.05$).

DISCUSSION

The purpose of this study was to investigate the effect of a rotating sound on postural regulation of human subjects. The influences of sound source velocity and of its sudden immobilization were compared to two control conditions: no sound and stationary sound in front of the subject. During the trials, subjects had to count the number of laps completed by the sound source.

Firstly, it was observed that the subjects successfully completed their counting task. This means that they perceived sound sourcedisplacement and were able to localize it throughout the trial.

Secondly, the overall observation was that amplitude of subject body sway and mean sway velocity were significantly smaller with a rotating sound than with stationary sound or no sound. Because subjects were deprived of visual cues and had their feet joined (leading to a reduced polygon of sustentation), the task was quite challenging.In this context, the modificationsin sway parameters(reduction of sway amplitude and velocity) mean that subject postural control was improved in the presence of moving sound: indeed, more efficient postural control is characterized by low mean velocity (expressing low energy consumption) and a small area covered by the COP movements (conveying precision of control) (Perrin et al. 1999; Era et al. 1996). In the literature, the opposite trend has been observed in a few studies, in which moving sound was found to have a destabilizing effect (SoamesandRaper 1992; Tanaka et al. 2001; Deviterne et al. 2005). This is not the case in presence of biofeedback (Chiari et al. 2005; Dozza et al. 2007; Davis et al. 2010) (i.e. when sound stimuli are modified in real-time, depending on subject movement). Similarly, for vision and posture interactions, a moving visual stimulus never helps stabilization (Mergner et al. 2005). However, the methodology of the present study was significantly different from that of previous studies. Firstly, in this study, subjects were naïve and implicated in a listening task, contrary to other studies where subjects were asked to stand as still as possible, and so implicated in a postural task. Secondly, inSoames and Raper (1992), the sound trajectories were different: from left to right and from font to back, which are not immersive trajectories like the circle in our experiment.Movement of the sound source was created by switching a 250-Hz tone from one loudspeaker to the other one every 10 sec. Rather than a continuous movement, this stimulation method seemed to gave the sensation of a sound source jumping from location to location, which can be expected to cause different reactions.Finally, for Tanaka et al. (2001) and Deviterne et al. (2005) subjects were elderly people who are known to have a poorer postural control.

Thus, sound seems to be taken into account by the central nervous system and integrated into the postural control process. Furthermore, a time before stabilization of about 7 seconds was observed with moving sound,compared with 3.5 seconds for no sound. This might suggest that subjects needed time either to integrate the auditory information or to free themselves from it. However, when the regularity of the sound stimuli was broken (by its sudden immobilization), thisimmediately disrupted the postural regulation that had been induced by the rotating sound. Immobilization of the sound source induced a sudden increase insway velocity, represented by the v_{leap} parameter. This seems to confirm that subjects integrated and used auditory cues to better stabilize, rather than that they had to free themselves from them.

To explain this stabilization, it is suggested that subjects used the auditory cues provided by sound stimulias additional sensory information helping them in their postural regulation. Here, the auditory cues involved were mainly binaural cues (ILD and ITD), which allow localization of the sound in the horizontal plane by using differences in the temporal and intensity characteristics of the sound, and monaural cues (spectral cues), which enable differentiation of sounds from in front and behind.The stabilization was more pronounced with a moving sound source because it is known that moving sound can be localized more precisely and more easily than stationary sound (Aytekin et al. 2008). Thus, subjects may have been stabilized via an auditory anchorage effect (Deviterne et al. 2005): the sound stimuli created a regular reference point for subjects. Here again, this is different from vision: visual anchorage is possible only with static stimuli. This interpretation of the stabilization may confirm that, in postural regulation, auditory cues are not used in the same way as visual cues.

Another explanation of the stabilization could be provided by the theory of Stoffregen et al. (2007), hypothesizing that posture can be modulated in ways that facilitate the performance of a perceptual task. In the present study, the counting task was perceptually demanding: subjects had to perceive sound source displacement to be able to count the number of laps. This theory would suggest that postural sway decreased to prevent interference with this perceptual task.

Next, it was observed that the sound source rotation velocityhad an effect on the various parameters studied. The faster source was rotating thegreater the decrease in subject body sway, and the greater the disturbance to their postural regulation when the sound was immobilized. The acceleration sound condition produced the same level of stabilization as the fastest rotation velocity condition (180°/s).This “velocity effect” could be explained by the level of attention required from the subjects. In a study performed on elderly subjects, Deviterne et al. (2005) showed that using a meaningful message (a story narrated by a recorded voice,which subjects were asked to remember) as the rotating stimulus led to a better subject postural control, compared to use of a pure tone. Their interpretation is that this improved postural regulation was due to the cognitive load added by the stimulus. Indeed, the attention paid by subjects to the sound stimulus in understanding the story being told forced them to take into consideration the regularity and rotation of the stimulus and allowed them to use it as an auditory anchorage. The present study also added a cognitive load to the subjects: they had to 1 - track sound source displacement and 2- count the number of laps completed by the sound.These two parts of the counting taskare related to two fundamental types of attention, respectively perceptual attention (focus on an external stimulus) and reflective attention (when attention is oriented toward internal representation, here of the numbers) (Chun and Johnson 2011).Our paradigm contrasts with studies where subjects only had to stand as still as possible (Soames and Raper 1992; Tanaka et al. 2001). In the present study, subjects were focused on sound stimuli, especially as they were blindfolded, and had only the counting task to perform. Many studies have addressed the role of cognitive load on postural regulation. Their results are conflicting, but these differences could be explained by the type of cognitive load used (Riley et al. 2003). Studies using the same type of cognitive load as in our experiment (i.e. mental tasks without any motor task or visual fixation) showed that a concurrent cognitive task helps to reduce the amplitude of body sway. Moreover the harder the task, the greater the reduction in sway (Riley et al. 2003; Vuillerme and Vincent 2006; Stins et al. 2011). Thus, it can be assumed that the stabilization observed is only due to focus on the listening and counting task. The velocity effect would therefore be explained by the level of attention that subjects devoted to the task: the faster the sound was moving the quicker they had to follow sound source displacement and the quicker they had to count. Similarly, the sudden change observed at sound immobilization could be due to the fact that subjects no longer needed to focus on the sound to perceive displacement of sound source and to count the number of laps. However, it has been reported elsewhere that in presence of a cognitive task, sway amplitude is reduced but sway velocity generally increases (Stins et al. 2011), which is not the case here. In any case, it would be interesting to better manage subject focus under various conditions, in order to separate the contributions of sound perception from those of cognitive tasks.

CONCLUSION

In this study, a rotating sound source was observed to have a stabilizing effect on the postural sway of subjects,which improved as sound source velocity increased.This result confirms that sound plays a role in postural control and must be taken into consideration alongside other sensory modalities. Understanding and characterizing this role opens the door to multiple applications, such as sensory substitution for blind people or patients suffering from vestibular disease, and reeducation and support for elderly people to prevent fall risks.

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